

The orbital motion of the Arches cluster – clues on cluster formation near the Galactic center

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Abstract. The Arches cluster is one of the most massive, young clusters in the Milky Way. Located inside the central molecular zone in the inner 200 pc of the Galactic center, it formed in one of the most extreme star-forming environments in the present-day Galaxy. Its young age of only 2.5 Myr allows us to observe the cluster despite the strong tidal shear forces in the inner Galaxy. The orbit of the cluster determines its dynamical evolution, tidal stripping, and hence its fate. We have measured the proper motion of the Arches cluster relative to the ambient field from Keck/NIRC2 LGS-AO and VLT/NAOS-CONICA NGS-AO observations taken 4.3 years earlier. When combined with the radial velocity, we derive a 3D space motion of 232 ± 30 km/s for the Arches. This motion is exceptionally large when compared to molecular cloud orbits in the GC, and places stringent constraints on the formation scenarios for starburst clusters in dense, nuclear environments.

1. Introduction

The Arches cluster formed in one of the most extreme star-forming environments in the Milky Way today. In the inner 200 pc of the Galactic center, the central molecular zone, a strong ambient UV radiation and magnetic field hamper cloud fragmentation, and tidal forces shear and disperse both clouds and young clusters on short timescales. Despite seemingly hostile to star formation, the central molecular zone hosts a substantial amount of several $10^7 M_{\odot}$ in dense, massive molecular clouds. In contrast to the more moderate, well-studied star-forming regions in the solar neighborhood, star formation in the GC environment is more representative of the massive starburst regions observed in the cores and bars of distant galaxies.

The Arches cluster is one of only three massive starburst clusters observed close to the Galactic center (GC), at projected distances < 30 pc. With an age of only 2.5 Myr (Najarro et al. 2004, Blum et al. 2001, Figer et al. 2002), it is in an almost pristine stage of cluster evolution, while its older twin, the Quintuplet, appears already dispersed at an age of 4 Myr as a consequence of its rapid dynamical evolution in the GC tidal field. The third known young, massive cluster is the central cluster located in the inner few parsecs around the supermassive black hole (SMBH), which comprises stars with ages of ~ 6 Myr (e.g., Paumard et al. 2005).

As the immediate environment around the SMBH is tidally heated and inhospitable to star formation (Morris et al. 1993, Ghez et al. 2003, 2005), star clusters forming at larger radii were suggested to spiral into the central parsecs and replenish the young population. The in-spiral scenario has recently been strengthened by the detection of dense groups of young, comoving stars in the central parsec (Lu et al. 2005, Paumard et al. 2006). With the observation of the space motion of the Arches cluster, we can probe the in-spiral scenario for this cluster directly.

2. Observations and geometric transformation

Keck/NIRC2 laser-assisted adaptive optics K' observations taken in July, 2006, were combined with VLT/NAOS-CONICA (NACO) HK_s data obtained in March, 2002. The final resolution on the combined image was diffraction-limited at the Keck 10m dish with 53 mas (FWHM) in the 18 minute K' exposure, and a resolution of 84 mas (FWHM) was achieved in the 7 minute NACO K_s frame. A detailed description of the data reduction and analysis can be found in Stolte et al. (2008). The geometric transformation between both images was fitted with a 2D second-order polynomial derived from bright stars on the Arches main sequence, with a final astrometric mapping uncertainty of 2 mas (rms). Proper motions were then measured in this cluster reference frame over the 4.3 yr baseline of the observations.

3. The Arches cluster proper motion

The proper motion diagram of stars in the central 10 arcseconds of the Arches cluster core is shown in Fig. 1. Cluster member candidates are clustering around zero motion in the cluster reference frame, while field stars scatter to proper motions as large as 10 mas/yr. The majority of field stars, however, is found in the south-west quadrant in proper motion space. As the field population is dominated by bulge stars in the inner Galaxy, a random distribution of orbital velocities is expected through the line of sight. The clustering of field proper motions to the south-west in the cluster reference frame can be interpreted as the proper motion of the Arches to the north-east with respect to the field. The proper motion of the Arches is measured from the mean of the field distribution in the south-west quadrant of the proper motion diagram to be 212 ± 29 km/s.

A possible concern arises in the bias of field stars to the near side of the bulge. As the near side of the central bar rotates from west to east, field stars on the near side display predominantly eastward motion, in the opposite direction to the observed velocities, which decreases the apparent motion of the cluster relative to the field. Therefore, the derived proper motion of 212 km/s is a lower limit to the absolute cluster velocity. Combination with the radial velocity of 95 ± 8 km/s (Figer et al. 2002) results in a 3D space motion of 232 ± 30 km/s for the Arches.

4. Formation scenarios for the Arches

With a total stellar mass of $\sim 10^4 M_\odot$, the two-body relaxation time of a GC starburst cluster at a distance of 30 pc from the center is on the order of a Gyr. With ages as young as a few Myr, the central starburst clusters should still move with the inherited velocity from their natal clouds. Clouds on stable orbits in the central molecular zone ($r_{GC} \leq 200$ pc) are suggested to follow spheroidal x2 orbits in the Milky Way bar potential (e.g., Binney et al. 1991, Englmaier and Gerhard 1999). Molecular clouds with high densities capable of massive cluster formation display line-of-sight velocities of $v_{los} < 120$ km/s in radio CS surveys (Dame et al. 2001). A velocity of 120 km/s is in agreement with the terminal velocity of x2 orbits in the Milky Way bar potential. These velocities are a factor of two too low to explain the high orbital motion of the Arches cluster. While the formation of the cluster is mysterious, the most likely trigger to form a high-velocity cluster appears to be a collision of two massive clouds (Stolte et al. 2008). Such a scenario was suggested as the triggering event for the burst of star formation in Sgr B2

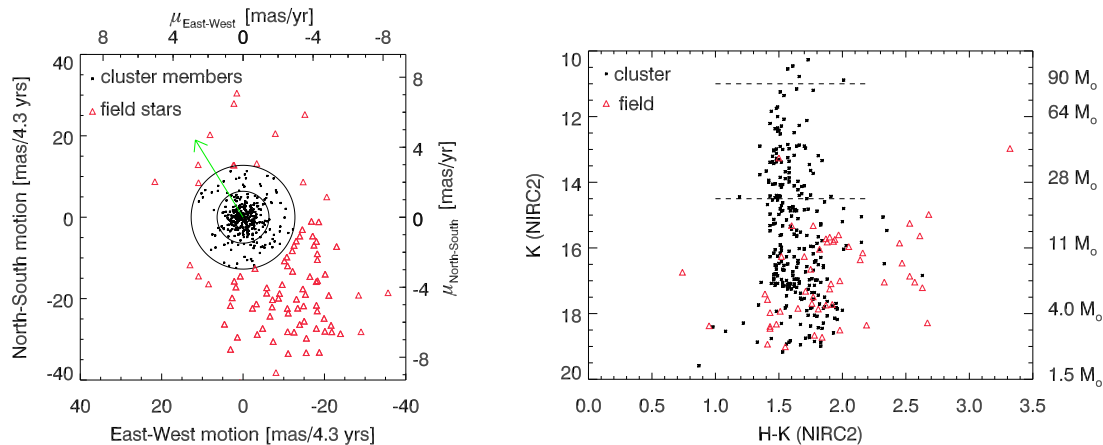


Figure 1. Left: Proper motion diagram of the Arches cluster. In the cluster reference frame, member candidates cluster around zero (dots), while field stars scatter to motions as large as ~ 10 mas/yr (triangles). The field populations is dominated by relative motion to the south-west, from which the cluster proper motion relative to the ambient field is derived to 212 ± 29 km/s to the north-east and parallel to the Galactic plane.

Right: Proper motion rejection of field contaminants in color-magnitude space. Triangles (red) mark field stars, while dots (black) represent a cleaned sample of cluster candidates. In particular, red clump stars in the bulge are identified as non-members at $K = 15.6$ mag, and the cluster sequence is cleaned at the low-mass end, where contamination is most severe.

(Hasegawa et al. 1994). However, this study suggests that the rate at which high-velocity clouds could migrate inwards from larger GC distances is not well constrained. Candidates for such a collision are clouds on x1 orbits following the bar's major axis outside the x2 (minor axis) orbital zone, as already suggested by Binney et al. 1991, or clouds falling in from the outer parts of the Galaxy (Crawford et al. 2002). A collision between an x1 and an x2 orbit cloud is particularly intriguing, as x1 clouds display line-of-sight velocities of up to 270 km/s (Dame et al. 2001), which could account for the orbital velocity of 232 km/s observed for the Arches today. One particular problem with this scenario is that the cluster would need to inherit the high velocity of the infalling cloud, which requires a massive, high density cloud capable to transfer its momentum to the local cloud on the x2 orbit. While this scenario would explain the observed velocity vectors of the Arches proper motion, molecular clouds on bar orbits outside the central molecular zone ($r_{GC} > 200$ pc) do not display high-density material in present-day radio maps, and would thus not be able to dominate the kinetic energy transfer during such a collision. This implies that either the colliding cloud does not originate from the pool of clouds on stable bar orbits, or that clouds with higher density were present at the time of the cluster's formation 2.5 Myr ago, but are not observed anymore at the present epoch. These caveats deepen the mystery of the formation of the Arches cluster.

5. The orbital motion in the GC potential

We have modeled the GC potential using logarithmic potential approximations (see Stolte et al. 2008 for details). The enclosed mass vs. radius relation was fitted by taking into account the gravitational potentials from the nuclear stellar cluster, the thick nuclear stellar disk, and the central black hole, as recently determined by Launhardt et al. 2002. Beyond the thick stellar disk, at $r_{GC} > 200$ pc, the potential was smoothly transformed to the bar potential, which

was approximated with a logarithmic potential as well, to ensure continuity in the test particle acceleration. The Arches cluster was evolved in this potential forwards and backwards in time with the aim to constrain the GC distance of the cluster's origin and the possibility for the Arches to reach the inner few parsecs from the black hole.

With knowledge of all three velocity components and the projected position of the Arches on the sky, the only unknown phase space coordinate is the line-of-sight distance of the cluster with respect to the Sun or the GC. In Fig. 2, a sample family of orbits is shown for line-of-sight distances of -100, -80, -60, -40, -20, 0 with respect to the location of Sgr A*, assumed to be the gravitational center of the inner Galaxy.

The orbital simulations reveal that the Arches can only reach the inner 10 pc around the SMBH if its absolute GC distance is very close to its projected distance, i.e. if the cluster has a negligible line-of-sight radius component with respect to the GC. Even on the most radial orbit, the cluster will not come closer to the SMBH than 10 pc, and has also not been closer to the SMBH during its lifetime. This limits the amount of tidal stripping in the high-density environment of the nucleus, and implies that the Arches does not contribute any young stars to the young stellar population near the SMBH. The observed 3D velocity of the cluster provides the first direct observational evidence that Arches-like clusters do not spiral into the GC during the lifetime of the massive stars, which is in excellent agreement with earlier N-body simulations based on assumptions on the initial cluster mass and the radial velocity alone (e.g., Kim and Morris 2003).

These simulations suggest that the Arches and Quintuplet clusters are not sufficiently massive for in-spiral (Gerhard 2001, Kim and Morris 2003). As a consequence, this implies that we do not observe any progenitor clusters for the GC cluster at the present epoch. Nevertheless, it cannot be excluded that a substantially more massive young stellar cluster formed 6 Myr ago in the inner few parsecs and migrated inwards to provide the young stars observed in comoving groups in the central parsec. Alternatively, the young stars could have formed in a massive, thick disk overcoming the tidal forces near the SMBH (Nayakshin et al. 2007). In any event, the observational constraint excluding Arches-like clusters as the source for young stars in the GC supports local star formation in the inner few parsecs around the SMBH.

6. Conclusions and outlook

The measurement of the 3D velocity of the Arches cluster enabled the detailed study of cluster formation scenarios in the central molecular zone, and allowed for the simulation of the cluster orbit in the GC potential. The orbital analysis suggests that the Arches is very unlikely to pass through the inner 10 pc of the Galaxy, which implies that the cluster does not contribute young stars to the stellar population near the SMBH. If located inside the central molecular zone ($r_{GC} < 200$ pc), the orbital simulations suggest that the cluster completed between one quarter of an orbit and at most one full orbit around the GC. The rapid motion of the cluster through the high-density environment in the GC might influence the tidal stripping of stars, and thus the dynamical evolution of the cluster mass. We therefore caution that the observed present-day mass function of the Arches might not be the pristine initial stellar mass function at the time of cluster formation.

These findings should trigger a new set of dynamical simulations to constrain the evolution of the cluster population and the still mysterious origin of the Arches cluster.

With the Arches cluster as a test case, we have shown that proper motion membership is now feasible for starburst clusters out to distances of 8 kpc using high-spatial resolution observations. For the first time, this enables us to study the unbiased stellar content of starburst clusters both in the Galactic center region and in the spiral arms, where foreground contamination hampers the detection of the extended cluster halo. The initiated starburst cluster survey of Milky Way starbursts in different environments with Keck/NIRC2 and VLT/NACO will provide a more

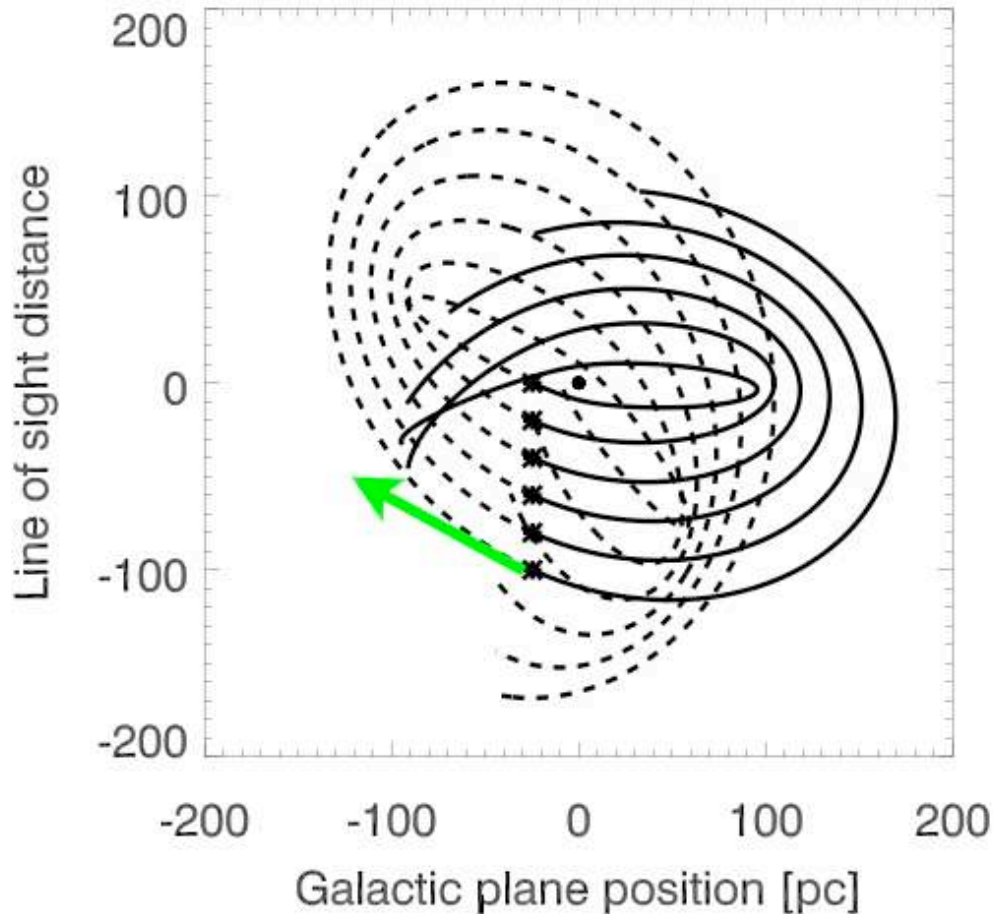


Figure 2. Simulation of the Arches orbit in the inner Galaxy. The SMBH is located at the origin, and the projection represents the view from above the Galactic plane, with the direction to the Sun at the bottom. The green arrow indicates the direction of motion of the Arches cluster. The figure represents a sample of line-of-sight distances of the cluster with respect to the GC from -100 pc to 0 pc in steps of 20 pc (asterisks). The orbit is integrated for 2.5 Myr backwards to the suspected origin of the Arches cluster (solid lines), and 360 degrees into the future (dashed lines). The dotted line approximates the location of the outer boundary of x2 orbits in the bar (Bissantz et al. 2003), assuming a bar rotation angle of 25 degrees (Rattenbury et al. 2007). Note that for these orbits with galacto-centric distances inside ~ 100 pc, an origin near the x2-x1 orbital boundary (dotted line) is possible, while a cluster origin near the x2 boundary becomes increasingly unlikely at larger galacto-centric distances.

complete census of stars and hence a critically closer approach towards an unbiased stellar initial mass function of Milky Way starburst clusters.

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